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STUDIES OF THE ELECTRICAL CHARGING OF THE TETHERED ELECTRON ACCELERATOR MOTHER-DAUGHTER ROCKET MAIMIK

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Abstract. The MAIMIK experiment was designed to study the charging of an electron-beam emitting payload using a tethered mother-daughter payload configuration. The particle accelerator on the daughter emitted short pulses of 8 keV energy electrons with a beam current which was varied in 6 steps from 20 to 800 mA. During the highest beam currents the accelerator payload was charged to potentials more than 50 per cent greater than the beam energy. It is speculated that a combination of a low background plasma density and a small payload may account for the apparently anomalous result.

Introduction

Rocket-borne accelerators have been extensively used in recent years to study the charging and neutralization of isolated space systems [Szuszczewicz, 1985]. During active electron emission, the electric potential which a rocket payload can attain relative to the local plasma depends on the total current balance of the vehicle and the disturbed plasma environment. Contrary to expectations from classical theory which place rather stringent limitations on the return current most accelerator payloads have achieved only modest potentials. However, a few payloads have reached sizeable potentials during electron beam injections [e g Jacobsen and Maynard, 1980], and even exceeded the nominal beam energy [Managadze et al, 1983 and Maehlum, 1988]. The conditions necessary to cause or prevent large vehicle potentials are not fully understood due to the complexity of the beam plasma interaction processes [Papadopoulos and Szuszczewicz, 1986] and the formation of high potential sheaths about the vehicle [Cooke, private communication, 1988].

One of the objectives of the MAIMIK program was to study the charging of a space vehicle during active beam injection. MAIMIK consisted of separate mother and daughter payload sections. The latter carried an electron accelerator.

In this paper we present some preliminary observations of the potential of the MAIMIK daughter together with a discussion of the unexpectedly high charging.

Instrumentation and geometry

The MAIMIK rocket experiment consisted of instrumented mother and daughter sections, which were separated at an altitude of 86 km with a relative speed of 0.8 m/s. During the separation the payloads axes were tilted at an angle of 23 degrees relative to the local geomagnetic field vector. Hence, the relative cross-field daughter velocity was 0.3 m/s. Both payloads reached an apogee of 381 km at 320 s.

The rocket was launched at 1856 UT (i e 1956 Local Time) on November 10, 1985 from the Andoya Rocket Range in Norway during geomagnetically quiet conditions. The European Incoherent Scatter Sounder EISCAT measured a background plasma density of only $10^4 cm^{-3}$ and an electron temperature less that 1500 K in the vicinity of the rocket.

The electron accelerator was mounted on the daughter, and the operation commenced at 98.0 s at an altitude of 164 km and persisted throughout the flight till rocket re-entry at 570 s. The two payloads remained electrically connected up to 112.6 s by an insulated stainless steel tether with a cross-section of 0.2 mm^2.

The outer surfaces of the mother and daughter were untreated aluminum, whereas the second stage of the rocket motor, which remained attached to the mother during the entire flight was made of stainless steel. The exposed surface areas for the daughter was 1.1 m^2, and for the mother/second rocket stage combination 9.7 m^2.

The daughter carried a Voltage Monitor (VM) and an array of Retarding Potential Analyzers (RPA). A three-axial set of electric field booms and plasma diagnostics instruments were located on the mother. An artist's conception of the two payloads is shown in Figure 1. For a detailed description of the MAIMIK experiment see Maehlum et al [1987].

The electron accelerator was comprised of five separate units which were operated in a current-limited diode configuration at a converter frequency of 610 Hz. The emission pulse duration was 11 ms, and the pulse repetition frequency 1.2 Hz. The accelerator potential relative to the daughter was 8 keV minus a small (less than 2 keV) voltage oscillation at the accelerator chopping frequency of 1.2 kHz. Separate gun pulses with nominal currents of 20, 40, 80, 160, 320 and 800 mA were injected normal to the daughter axis at pitch angles ranging from 62 to 117 degrees.

The VM circuit included the tether, which was attached directly to the mother payload ground and coupled through a 10 MOhm resistor to the daughter structure. The potential across this resistor was monitored at a sampling frequency of 3.7 kHz over the range from +5 V to -14 kV. The tether was programmed to be cut in the daughter at 130 s. However, due to the unexpectedly high charging of the daughter, the tether was cut prematurely at 112.6 s during an 800 mA pulse. Hence, only 15 pulses were recorded by the VM.

The RPA on the daughter consisted of an array of eight separate analyzer grids with fixed retarding potentials of 0 V, 12 V, 85 V, 180 V, 400 V, 800 V,

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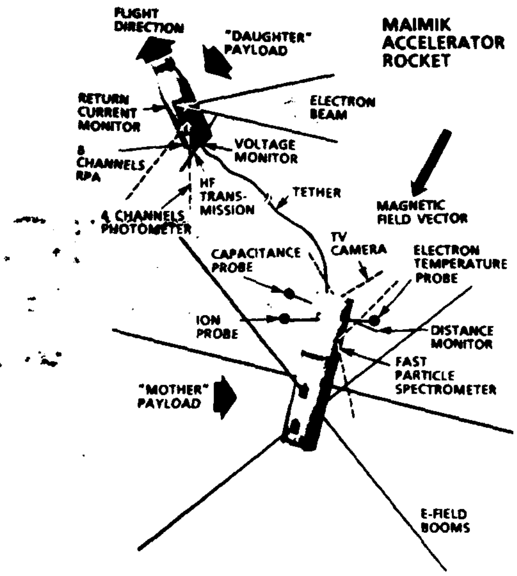

Fig. 1. An artist's depiction of the MAIMIK rocket experiment. The rocket attitude relative to the Earth's magnetic field is indicated by the local field vector.

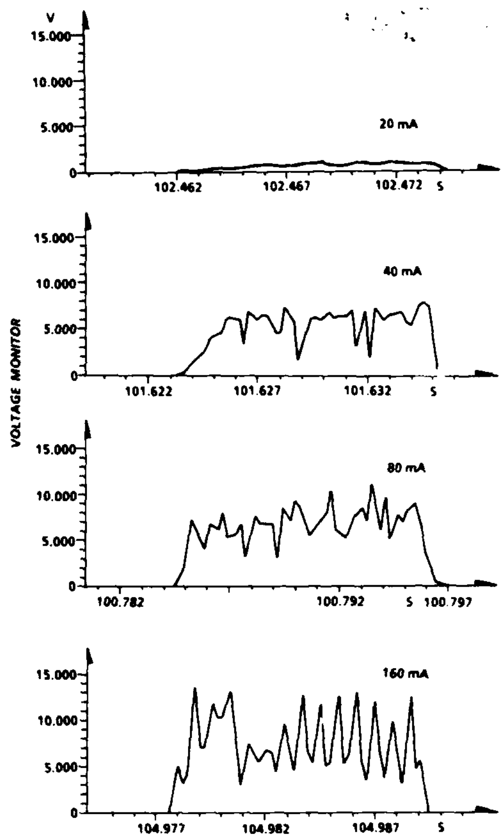

Fig. 2. The VM responses to four different pulse currents. Note the large oscillations in the potential during the 160 mA beam pulse.

1.6 kV and 3.2 kV relative to the daughter ground. The collecting area of each detector was 6.6 cm^2 and the minimum detectable current was 2.3 nA. The RPA was located at 90 degrees in a clockwise direction from the accelerator viewed from above. At low charging levels the observed energy cut-off response was comparable to the VM recordings (see Table 1). Unfortunately, charging levels above 3.2 kV were not foreseen prior to flight, and no direct comparison between the RPA and the VM can be obtained for the highest potentials.

Observations of vehicle charging

In Figure 2 we present the maximum charging of the daughter payload measured by the voltage monitor during all pulses before tether cut. A total of 15 pulses were recorded by the VM, but telemetry drop-outs occurred during the 800 mA injections. Note that the daughter potential apparently exceeded the beam energy by up to 50 per cent several times during this time interval. Such high vehicle potentials have, to our knowledge, never been recorded on accelerator rockets.

Table 1 Comparison between RPA energy cut-off and VM measurements during initial part of pulses.

Pulse No	Current mA	RPA threshold keV	VM kV
1	80	> 3.2	11.0
2	40	1.6 - 3.2	2.3
3	20	0.8	0.8
4	40	> 3.2	8.0
5	80	> 3.2	12.0
6	160	> 3.2	14.0
7	800	no telemetry	
8	320	> 3.2	14.0
		(0 - 12 V *)	(10.0 V *)
9	80	> 3.2	12.0
10	40	> 3.2	8.0
11	20	0.4 - 0.8	0.5
12	40	1.6 - 3.2	2.0
13	80	> 3.2	12.0
14	160	> 3.2	12.0

*) just after the end of the pulse.

A closer inspection of the individual pulses (Figure 3) reveals some features: First, the vehicle potential displayed a gradual increase just after the onset of the pulse, reaching a steady state value. This steady state is most pronounced for the lowest beam currents. The daughter potential reached an equilibrium value after some 6 ms for the 20 mA pulse, whereas the corresponding time constant for the 80 and 160 mA pulses was only 1 ms. For the highest beam currents the vehicle voltage showed large oscillations later in the pulse when the daughter achieved potentials greater than the accelerator voltage. The frequency of these oscillations was similar to the chopping frequency of the accelerator and was most likely driven by changes in the coupling between the highly charged daughter and the plasma caused by variations in the acceleration potential.

At the end of the pulse the potential declined rapidly (Figure 4). The voltage dropped by a factor of 10 - 100 within 0.5 ms. Just after one of the 160 mA pulses the vehicle potential was even reversed, similar to what has been observed by Arnoldy and Winckler [1981]. After a shortlived minimum the vehicle was apparently recharged some 6 ms after the end of the pulse, and for the highest beam currents this delayed charging reached a value of 10 - 15 V. Finally, the vehicle potential recovered slowly towards a small equilibrium value near zero over a period of 20 - 30 ms.

The relation between the beam current and the vehicle potential is shown in Figure 5, where the maximum and minimum values during individual pulses are plotted. Note that the beam energy of 8 keV was reached at a current of only 40 mA, and the vehicle potential was greater than 13 kV at a beam current of 160 mA, more than 5 kV above the nominal beam energy. The minimum potentials during the electron injections reached a plateau of 5 kV at a pulse current of 80 mA.

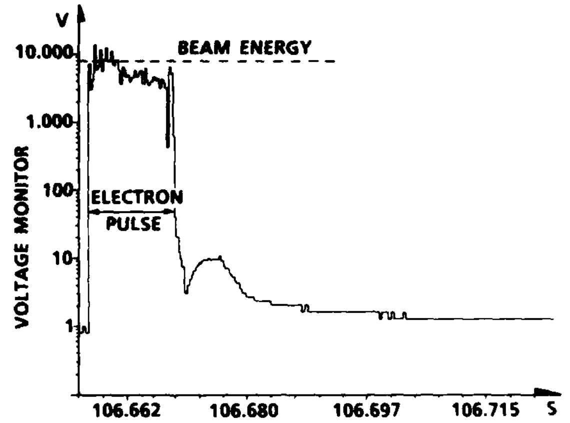

Fig. 3. Observed variations in the daughter potential during and shortly after a 160 mA pulse. The accelerator voltage is indicated by the broken line.

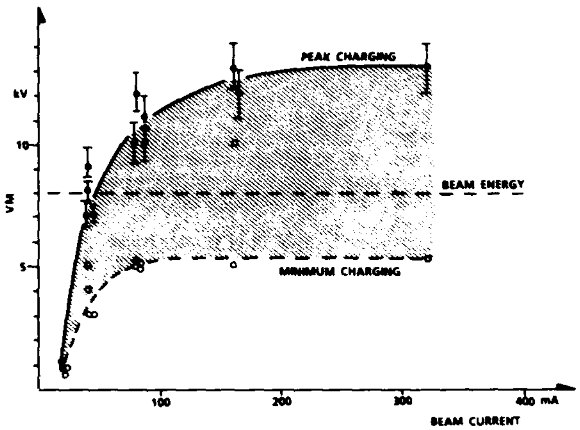

Fig. 5. Observed maximum and minimum values of the daughter potential during the beam injections as a function of beam current. The error bars refer to pre-flight calibration uncertainties.

Discussion

Differential voltage measurements using tethered vehicles [Sasaki et al, 1986; Maehlum et al, 1987] or long booms [Kawashima et al, 1982; Managadze et al, 1983] are perhaps the most reliable means for determining spacecraft potential. These techniques, however, provide only relative measurements and may not be adequately referenced to the local plasma potential. In the case of MAIMIK there were several compelling reasons to suggest that the potential reference did not significantly deviate from that of the undisturbed background plasma. Specifically, electric field measurements indicated that the reference vehicle was outside of the region of intense potential gradients and that the integrated radial electric field was, at best, only a minor contributor to the daughter payload potential. Also, it is unlikely that the tether upset the ground reference since the 1.3 mA of current which flowed through the 10 MOhm tether during the largest potentials was easily drawn from the surrounding ionospheric plasma by the large surface area of the mother payload. Most conclusive, however, was the rather strong agreement between the tether voltage measurements and the energy distribution of the returning electron flux within the instrument capabilities of the RPA (Table 1). Therefore the MAIMIK tether monitor was a true measure of the daughter potential relative to the background plasma. During electron beam operations this spacecraft potential achieved extremely high levels which at times exceeded the beam potential.

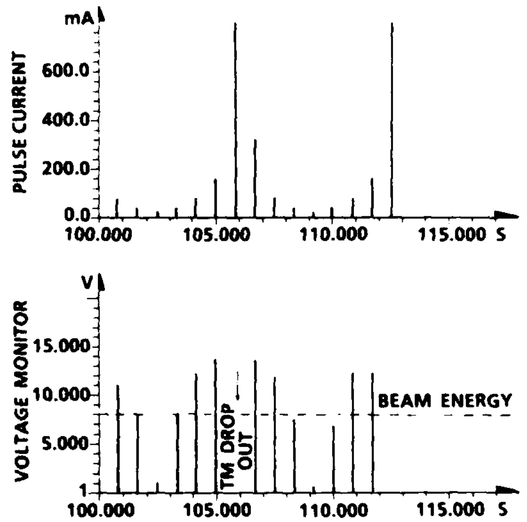

Fig. 4. Pulse currents and observed peak potential of the daughter during the first 15 pulses.

The measurement of a potential higher than the beam energy by some 50% does not easily lend itself to one's physical intuition. However, the processes which might result in such extreme charging are not without some physical basis or precedent. Recently, Denig et al [1987] have suggested that the seemingly anomalous charging results on MAIMIK may have been due to the formation of a virtual cathode; that is, a turbulent region of negative space charge, near the electron gun aperture. A virtual cathode is a naturally occurring phenomenon in the vacuum propagation of intense electron beams when the injected current flux exceeds the space-charge limit defined by the system geometry [Miller, 1982]. The high charging of electron gun systems have, at times, been tentatively attributed to virtual cathode formation in both laboratory [Kellogg, 1982] and space [Managadze et al, 1988] experiments. The turbulent behavior of the cathode and its finite location within the system may allow a percentage of the primary beam particles to escape and thereby drive the payload to a high potential.

Therefore, we suspect that the experimental parameters responsible for the high charging levels on MAIMIK were the high beam-to-plasma density ratio [Maehlum et al, 1987] and the small size of the daughter payload relative to other plasma scale sizes [Denig et al, 1987]. Recent numerical modeling efforts by Winglee and Pritchett [1987] have quite independently substantiated these ideas in principle. Specifically, these authors have shown that extremely large spacecraft potentials can be attained if (i) the time scale for virtual cathode formation is notably less than the plasma response time for establishing the return current flux to the spacecraft, and (ii) the physical size of the vehicle is less than the scale size of the return current area. Within the context of the MAIMIK experiment for a 160 mA, 8-keV beam emitted from a 2 cm aperture gun into an ionospheric plasma density of $10^4 cm^{-3}$ the ratio of the beam stagnation time to plasma response time was about 1/30. Also, the "effective" radius of the daughter payload was approximately 30 cm and significantly less than the 15 cm size of the return current region scaled from the numerical results. Thus it would appear that both necessary conditions for the high charging of an electron emitting payload according to Winglee and Pritchett were satisfied by MAIMIK.

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Plasma

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